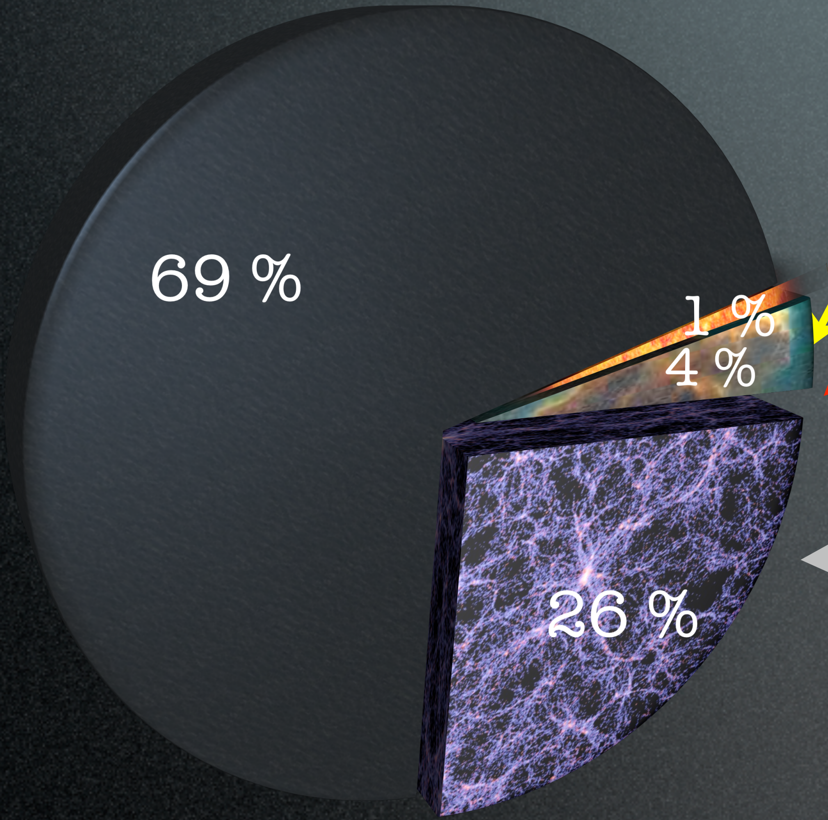
Energia Oscura

(Dark Energy)

How do we know that Dark Energy is out there?

The cosmic inventory

Most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$

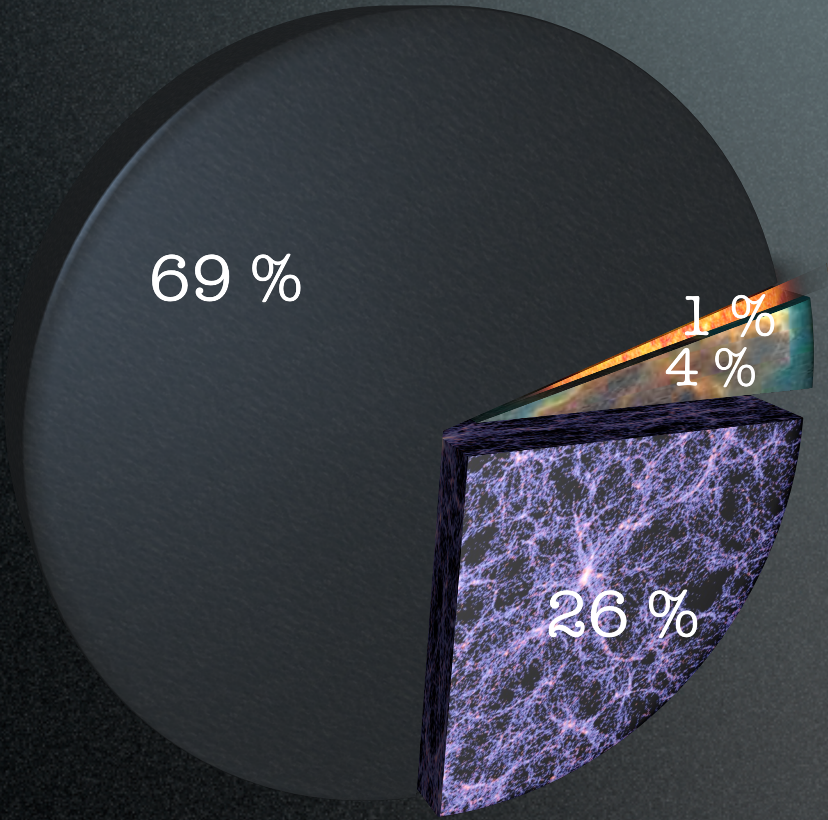
$\Omega_{\rm b} \simeq 0.040 \pm 0.005$

$\Omega_{\rm DM} \sim 0.26$

$\Omega_{\rm de} \sim 0.69$

The cosmic inventory

‘Definition’ of Dark Energy:



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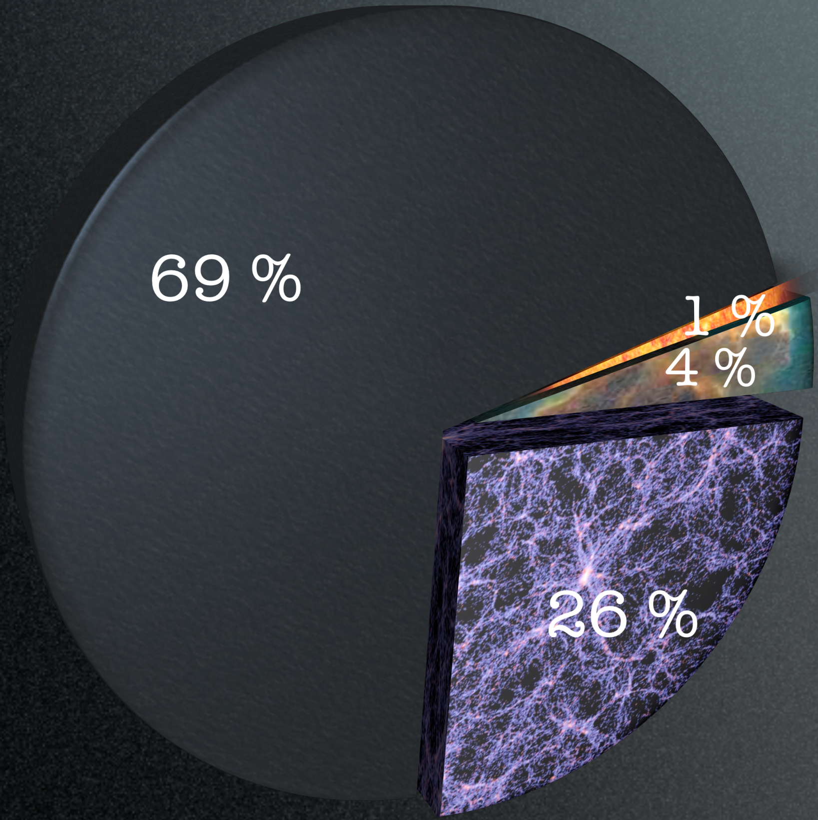


‘Definition’ of Dark Energy:

Einstein equations

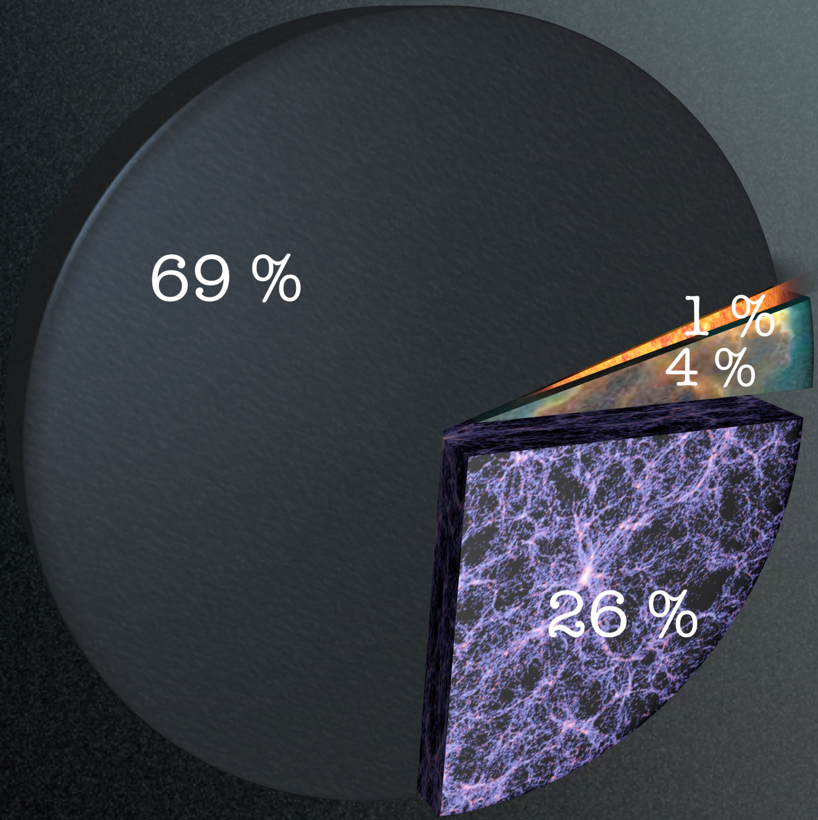
pressure

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

density

the ‘size’
of the Universe

The cosmic inventory



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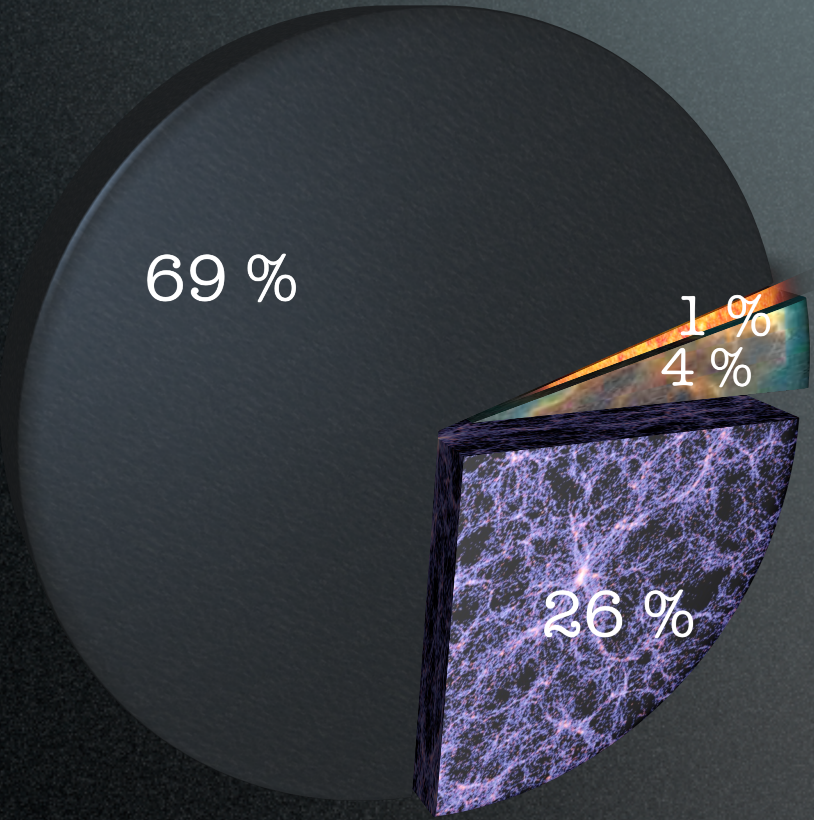
if $\rho < -p/3$ i.e. $w := \frac{\rho}{p} < -\frac{1}{3}$

⇨ acceleration!

The cosmic inventory



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$\Rightarrow$ acceleration!

special case:

$\rho = -p$ i.e. $w = -1$

cosmological constant Λ

(constant as $\rho_i \propto (1+z)^{3(1+w_i)} \rightsquigarrow \text{const}$)

The Evidence for DE

1) Supernovae type Ia:

‘standard candles’

$$\mathcal{L} = 4\pi F\, d_{\rm L}^2$$

Distance

Luminosity ('known')

Flux ('measured')

The Evidence for DE

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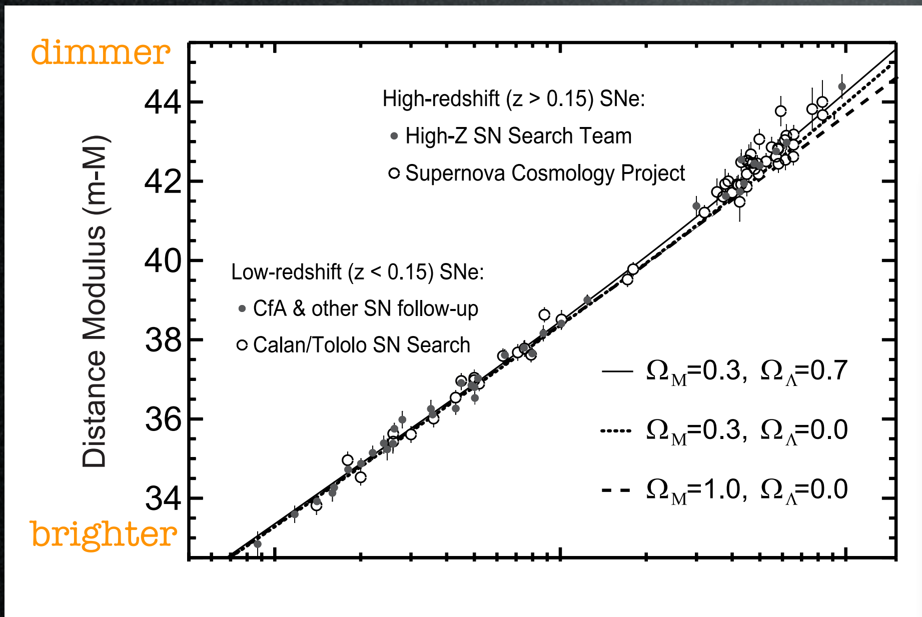
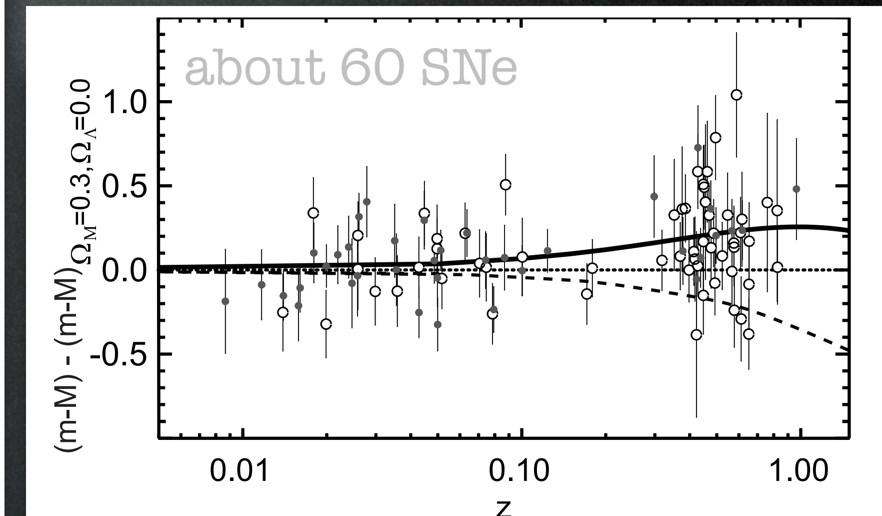


Perlmutter et al., 1999, Astrophys. J. 517
Riess et al., 1998, Astron. J. 116



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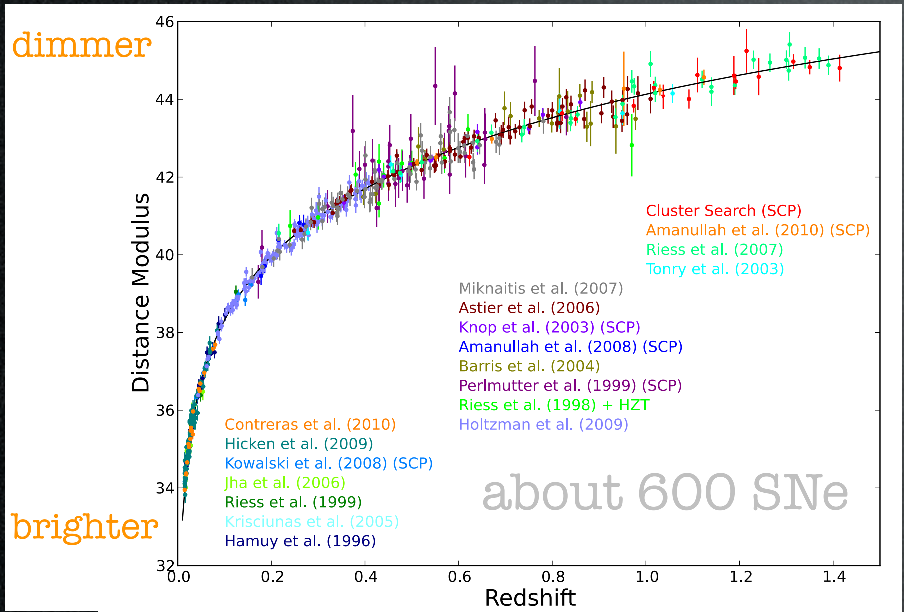


Suzuki et al., 1105.3470

Bottom line:

distant SNe appear dimmer than predicted in a Universe without DE,

the Universe has accelerated in the past 5 Gyr

The Evidence for DE

2) Baryon Acoustic Oscillations:

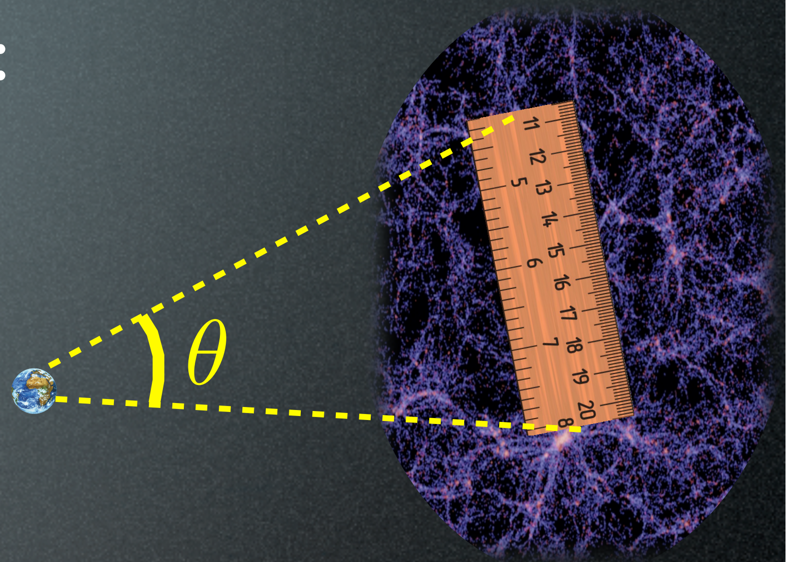
'standard ruler'

$$L = \theta\, d_{\mathrm{A}}$$

Length ('known')

Angle ('measured')

Angular distance ('unknown')



The Evidence for DE

2) Baryon Acoustic Oscillations:

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comoving distance ('unknown')

$$L = \theta\, d_{\mathrm{A}} = \theta\, \frac{\chi}{1+z}$$

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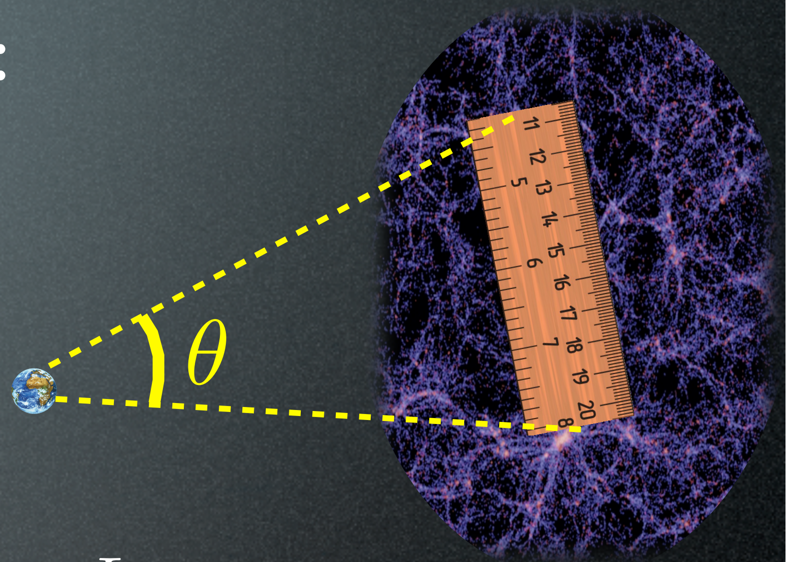

$$\chi(z) = \int_0^z \frac{dz'}{H(z)} = \int_0^z \frac{dz'}{H_0\sqrt{\Omega_{\mathrm{M}}(1+z')^3 + \Omega_\Lambda}}$$

so L as fnct of z and $\Omega_{\mathrm{M}}, \Omega_\Lambda$

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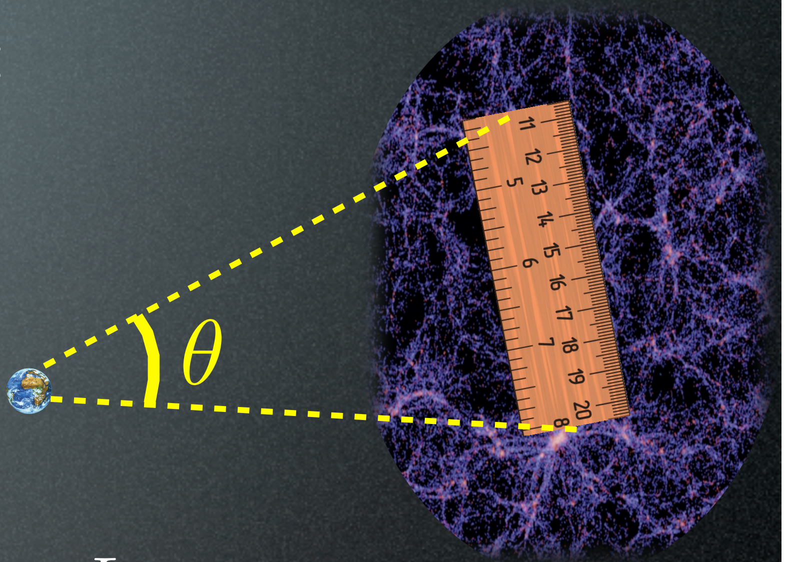

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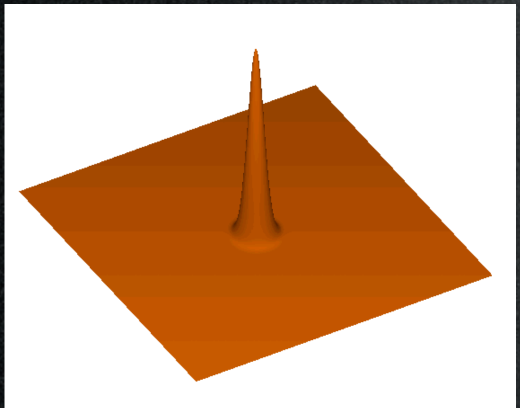

D.Eisenstein, cmb.as.arizona.edu/~eisenste/acousticpeak/

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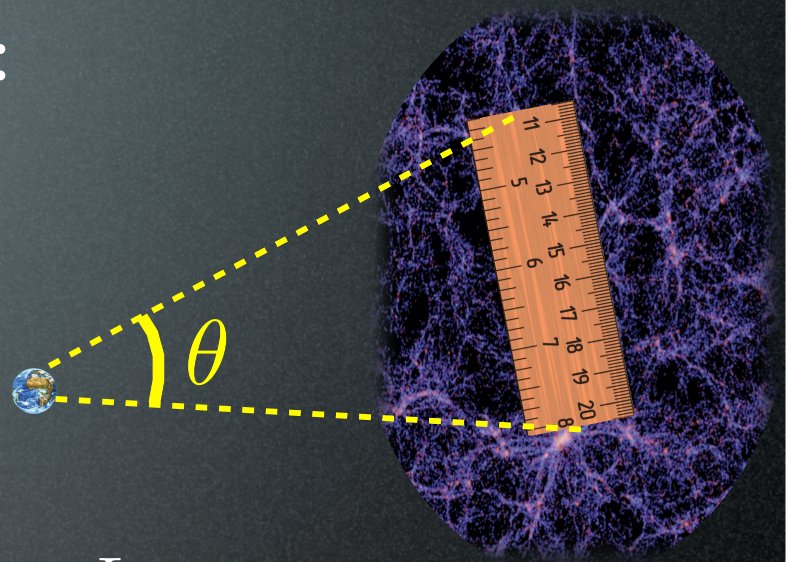

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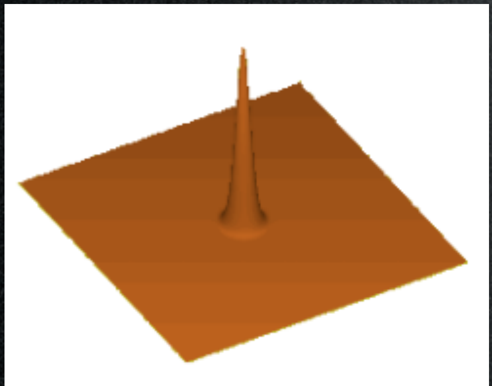

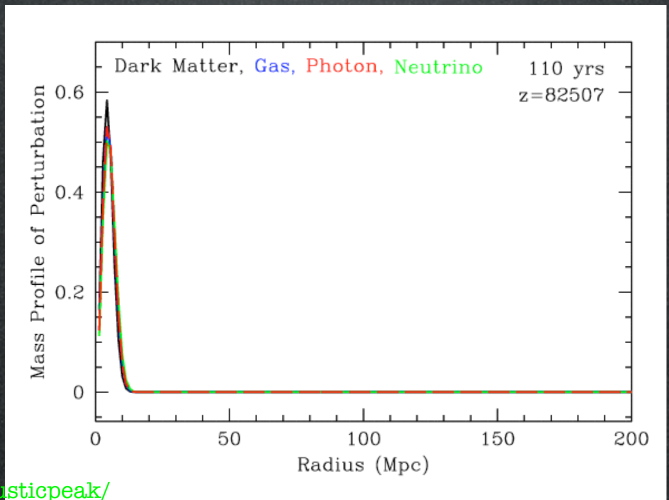

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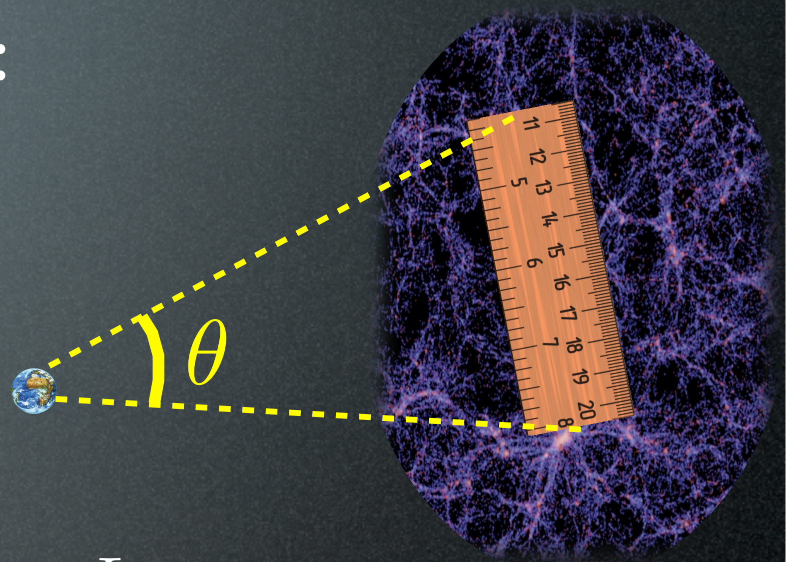

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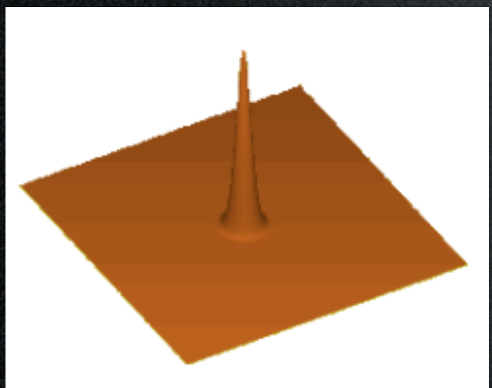

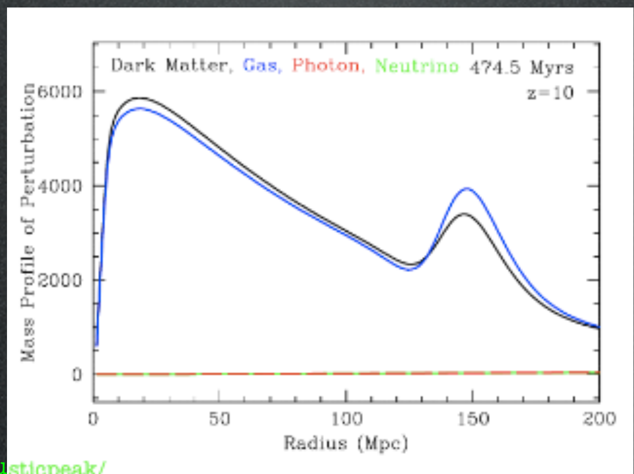

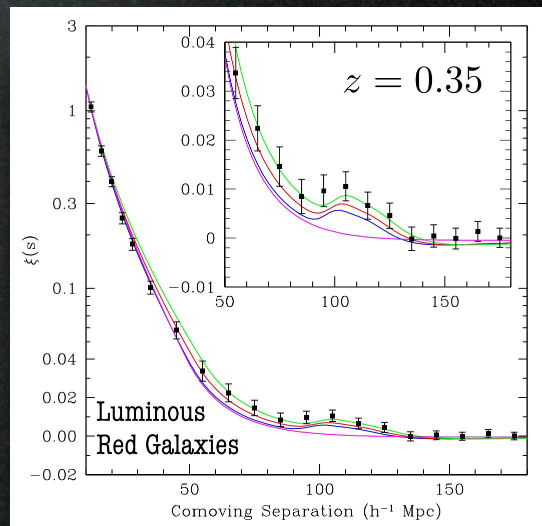

Eisenstein et al., astro-ph/0501171

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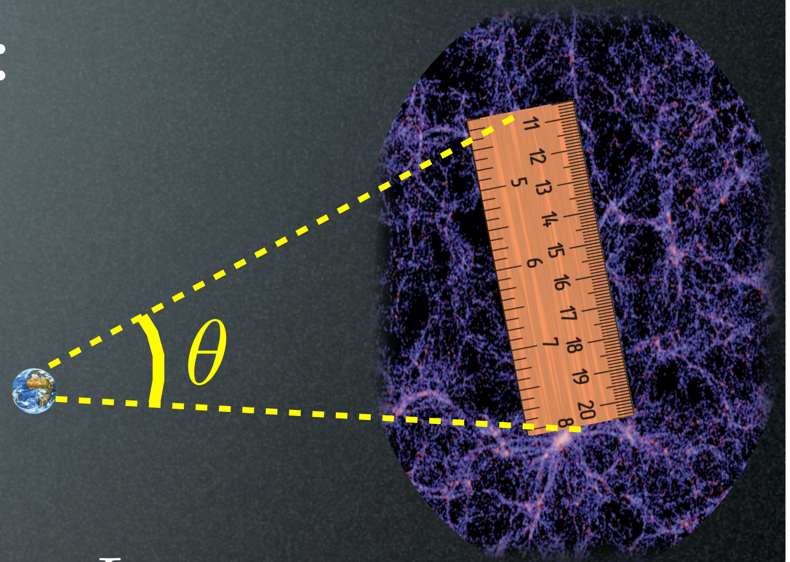

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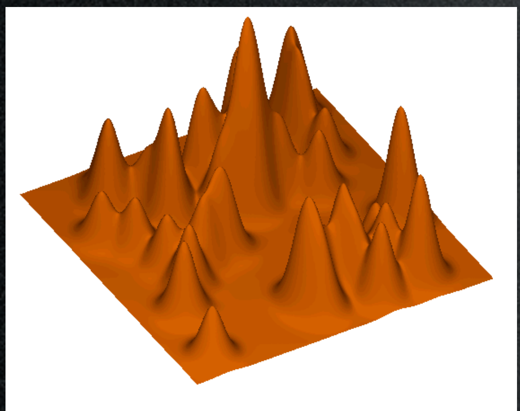
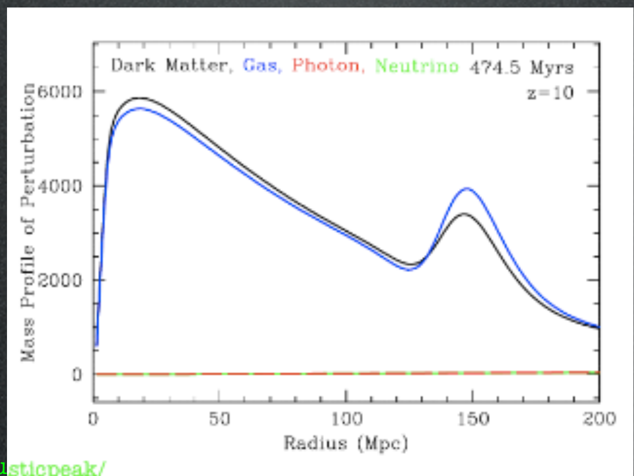
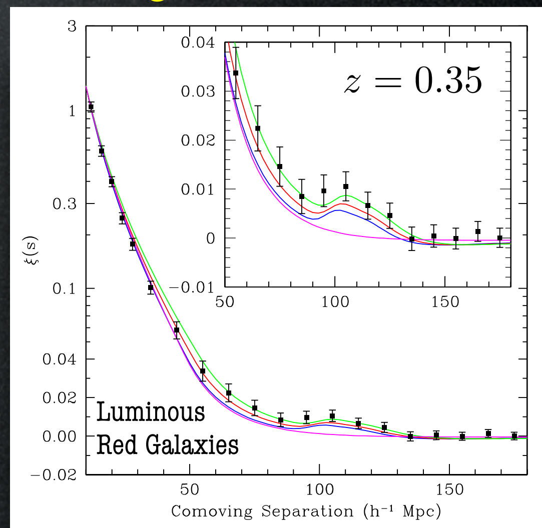
What is the ‘ruler’? A pinch in the galaxy distribution







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NB: can actually do the same in z direction

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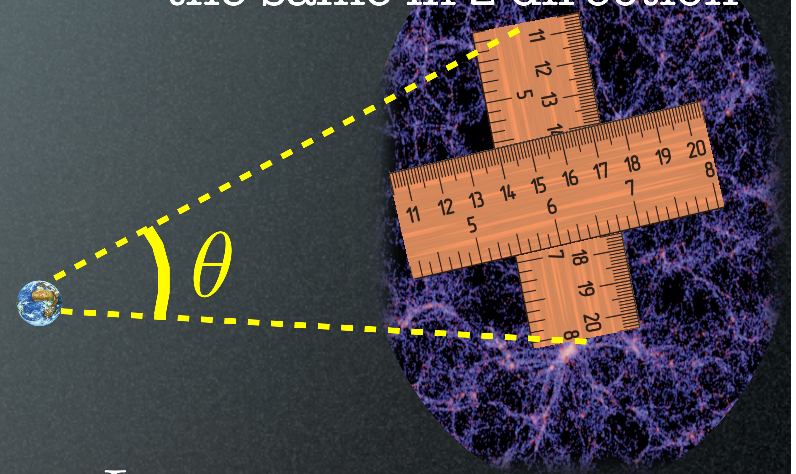

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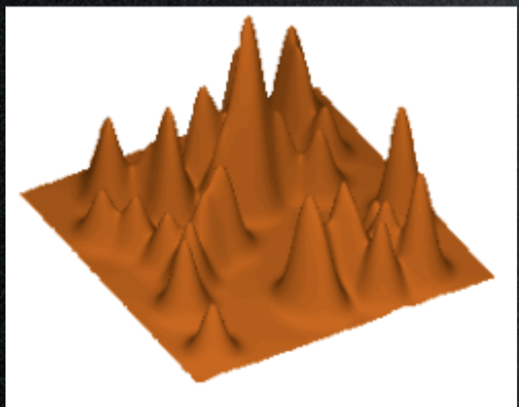

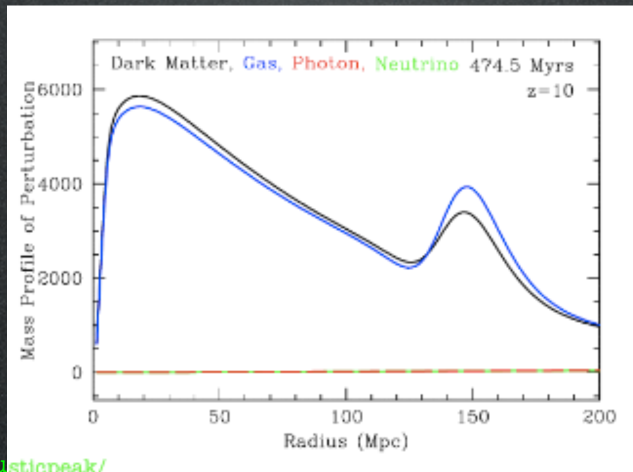

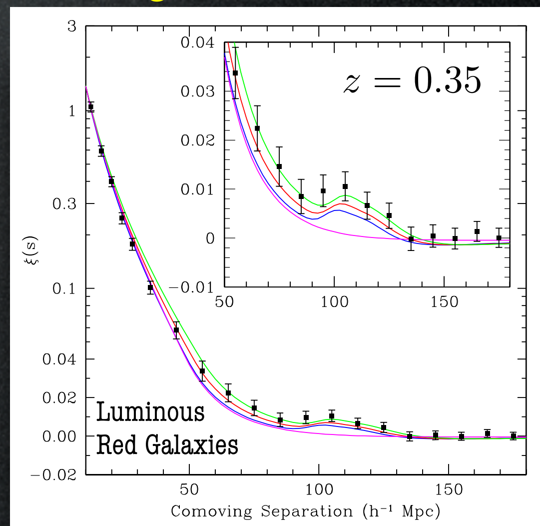

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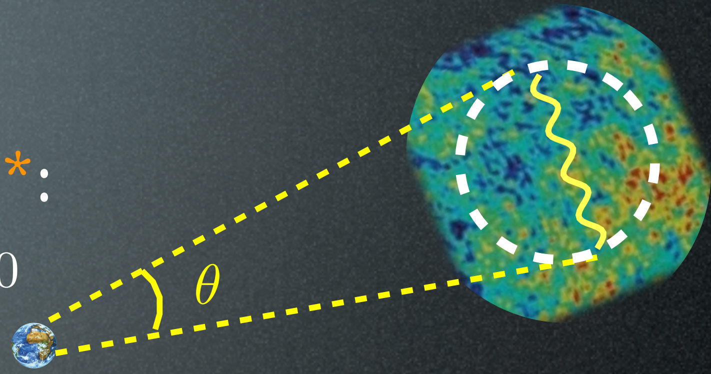
The Evidence for DE

3) CMB:

In principle: another 'standard ruler' *:

the size of the sound horizon at $z \simeq 1100$

$$r_s = \int c_s \, d\tau \qquad c_s \simeq c/\sqrt{3}$$



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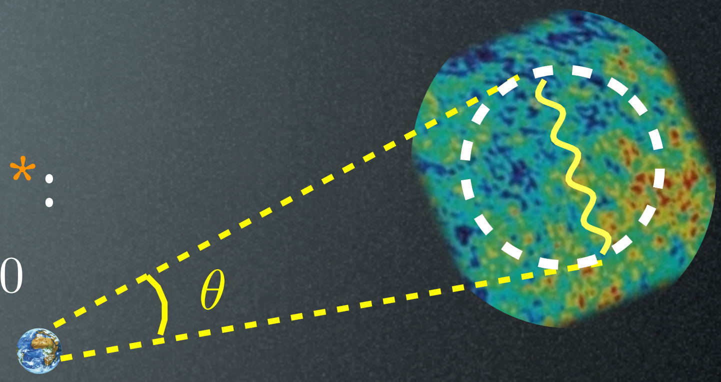

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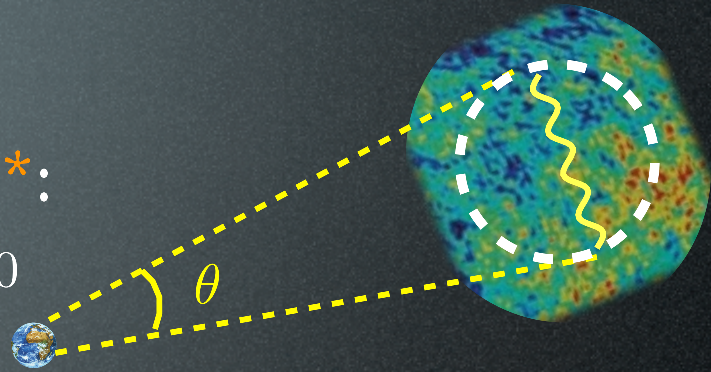

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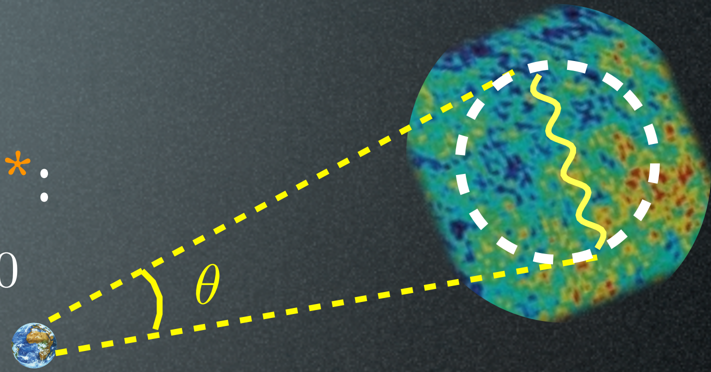

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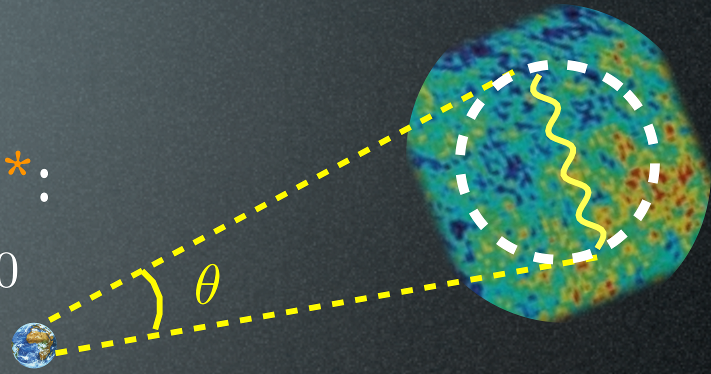

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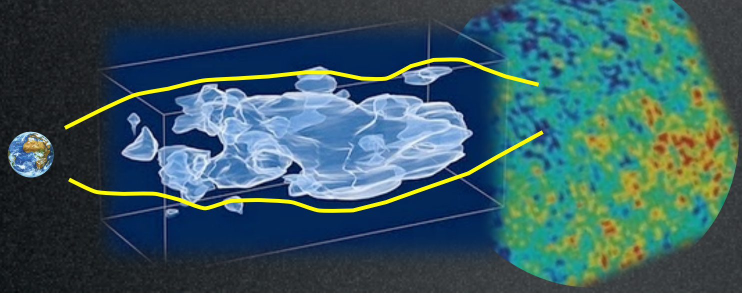
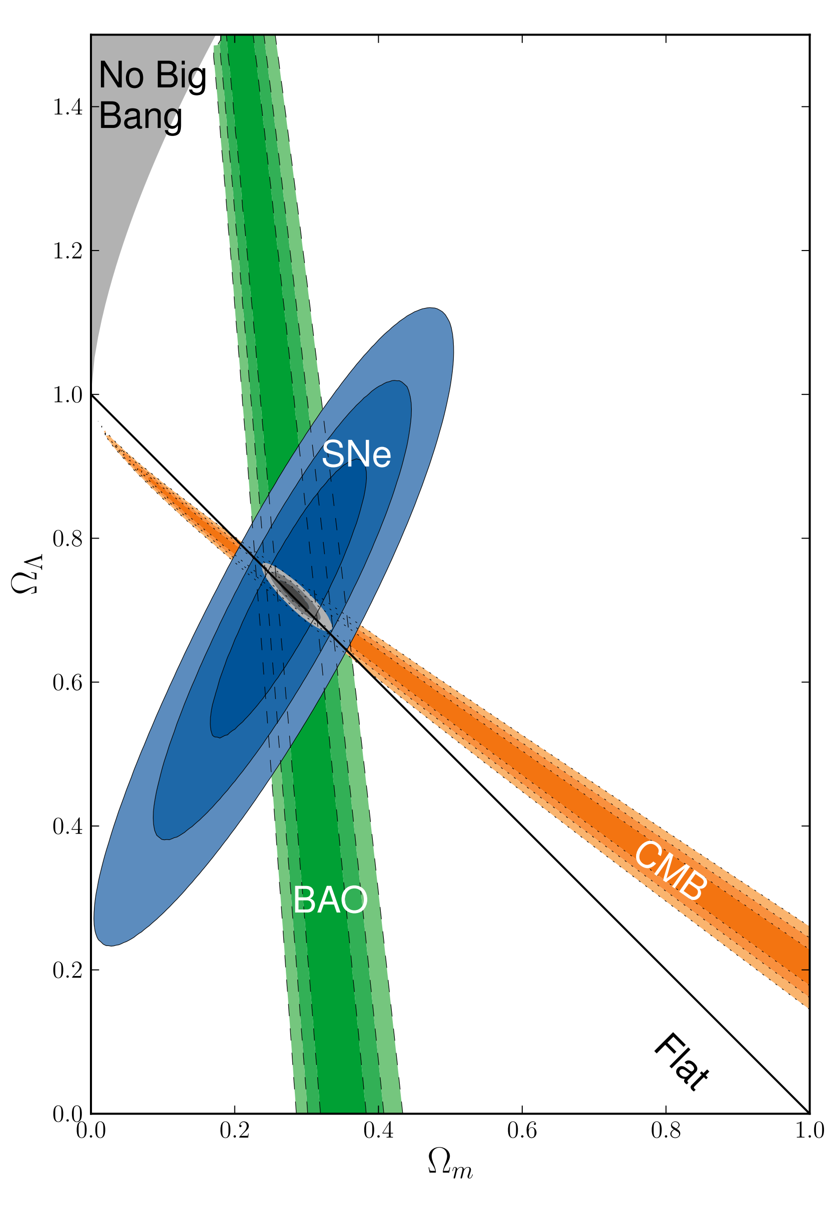
Moreover, recently: using weak lensing of CMB light



$$\Omega_\Lambda = 0.61^{+0.14}_{-0.06}$$

Sherwin et al., ACT Atacama Cosmology Telescope, 1105.0419

The Evidence for DE



Suzuki et al., 1105.3470

- complementarity
- concordance

$$\Omega_\Lambda = 0.725 \pm 0.016$$

$$\Omega_M = 0.274 \pm 0.007$$

Komatsu et al., WMAP7, 1001.4538

Other probes played / will play a role:
- cluster counts
- weak lensing...

What do we know of the (particle physics) properties of Dark Energy?

[redacted]

Nature of DE

Λ cosmological constant, $w = -1$

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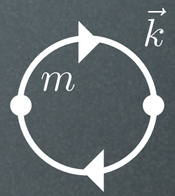
$$\simeq \sum_{\mathrm{particles}} \frac{g_i\, k_{\max}^4}{16\,\pi^2}$$



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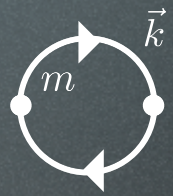

if $k_{\rm max} \sim M_{\rm Pl}$ $\quad \rho_\Lambda \sim 10^{74}\ \mathrm{GeV}^4$

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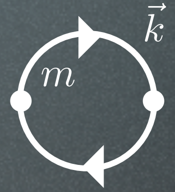

121 orders of magnitude!!

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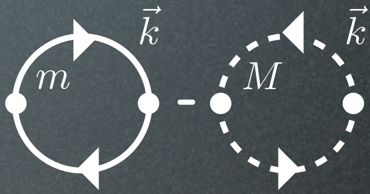

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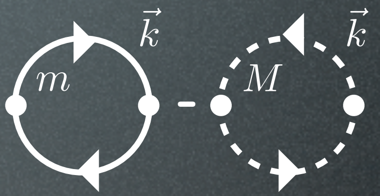

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The worst
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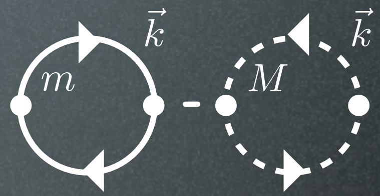

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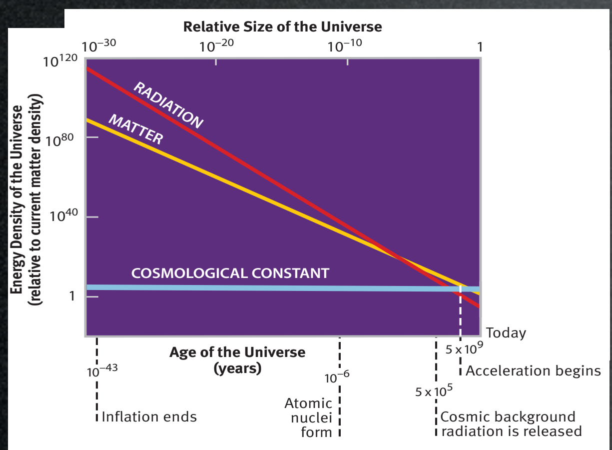
The worst fine tuning problem. Ever.

evolution in time



Nature of DE

Λ cosmological constant, $w = -1$

measured value $\rho_\Lambda = 2.5\ 10^{-47}\ \mathrm{GeV}^4$

estimate $\rho_{\rm vac} = \frac{1}{2} \sum_{\rm particles} g_i \int_0^{k_{\rm max}} \frac{d^3k}{(2\pi)^3} \sqrt{k^2+m^2}$

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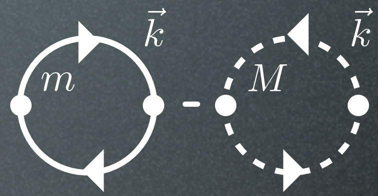

if $k_{\rm max} \sim M_{\rm Pl}$ $\rho_\Lambda \sim 10^{74}\ \mathrm{GeV}^4$

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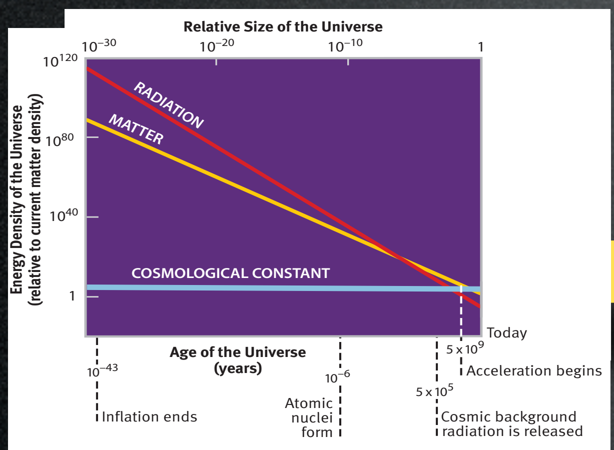

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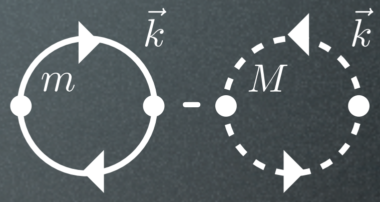

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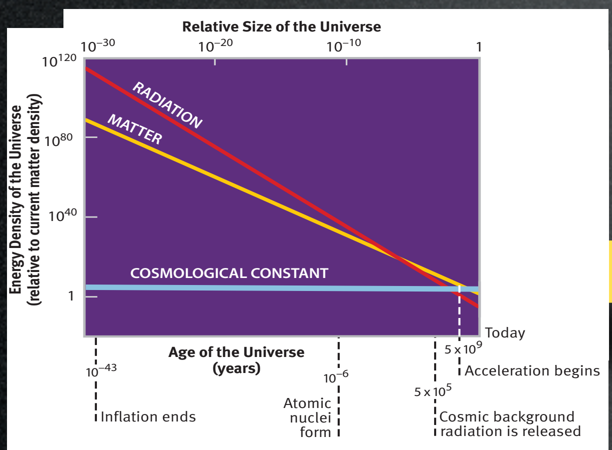

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Anthropism?

Multiverse?

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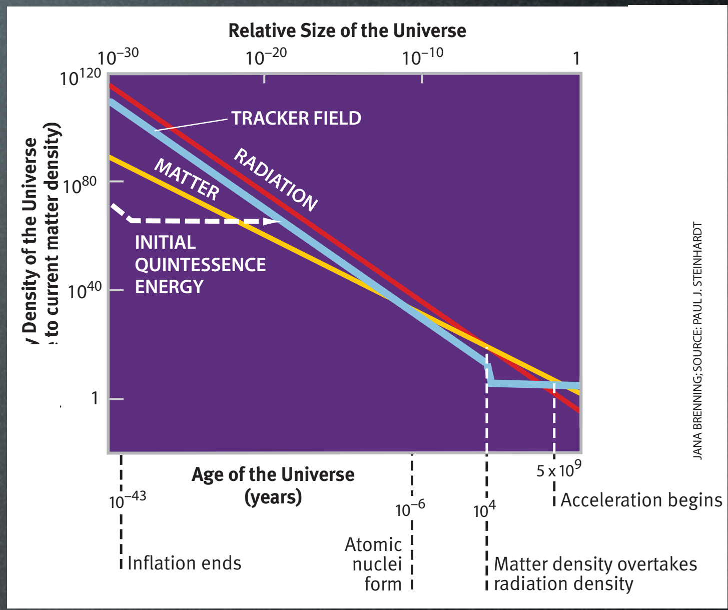

Ostriker and Steinhardt, Scientific American 2000

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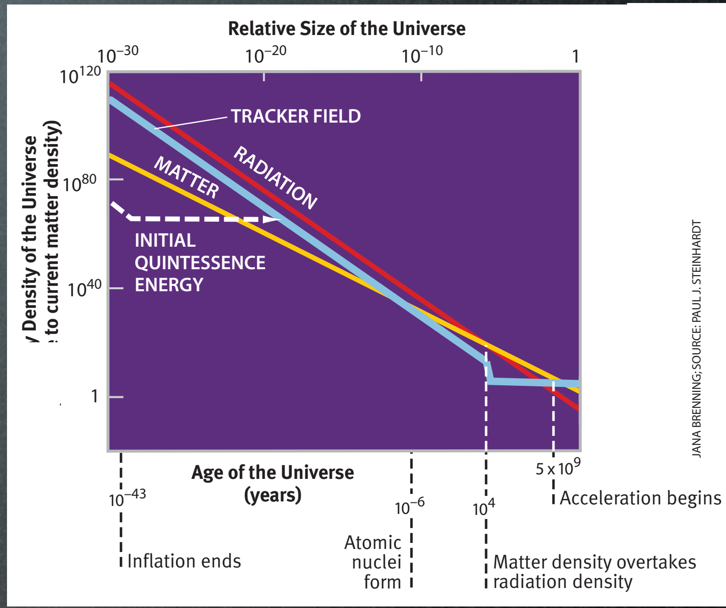

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Modified Gravity (f(R), DGP...)

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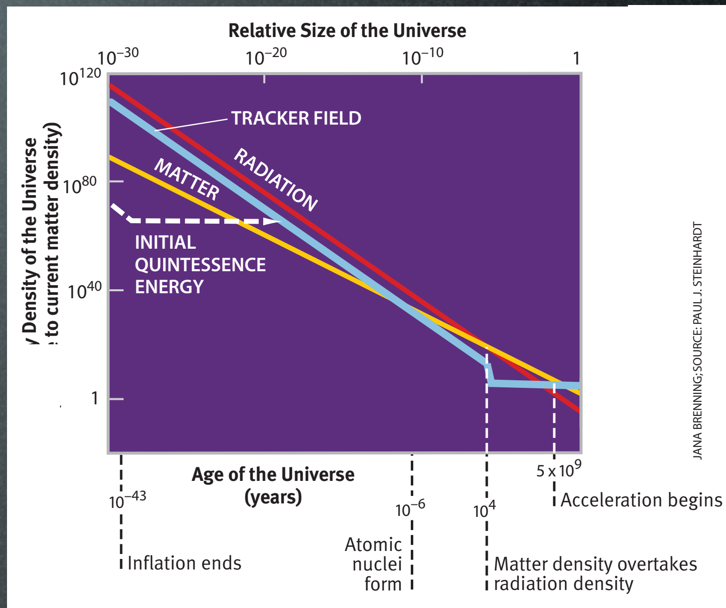

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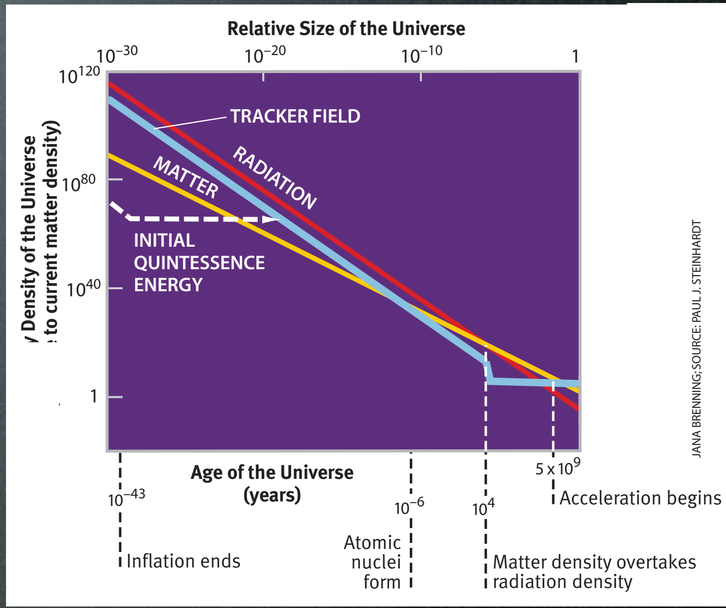

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